A Novel PFC Circuit for Reduced Switching Loss Bidirectional AC/DC Converter PWM Strategy with Feedforward Control for Grid-Tied Microgrid Systems

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Abstract-In this paper, a buck half-bridge DC-DC converter is used as a single-stage power factor correction (PFC) converter for feeding a bidirectional AC/DC converter. A simplified pulse width modulation (PWM) strategy is used for the bidirectional ac/dc single phase converter in a microgrid system. Then, the operation mechanism of the novel simplified PWM is clearly explained. The number of switchings of the simplified PWM strategy is one fourth that of the unipolar PWM and bipolar PWM. Based on the novel simplified PWM strategy, a feasible feedforward control scheme is developed to achieve better rectifier mode and inverter mode performance compared with the conventional dual-loop control scheme. The simplified PWM strategy with the feedforward control scheme has lower total harmonic distortion than the bipolar PWM and higher efficiency than both unipolar and bipolar PWMs. Furthermore, the simplified PWM operated in the inverter mode also has larger available fundamental output voltage V_{AB} than both the unipolar and bipolar PWMs. The proposed PFC converter improves the value of the output DC voltage of bidirectional AC/DC converter. The simulations are carried out in MATLAB/Simulink environment.

***Keywords**:* **Bidirectional ac/dc converter, simplified pulse width modulation (PWM) strategy, total harmonic distortion (THD), PFC.**

1. Introduction

The single-phase ac/dc pulse width modulation (PWM) converter is widely used in many applications such as adjustable-speed drives, switch-mode power supplies, and uninterrupted power supplies. The single-phase ac/dc PWM converters [1]–[11] are usually employed as the utility interface in a grid-tied renewable resource system, as shown in Fig. 1. To utilize the distributed energy resources (DERs) efficiently and retain power system stability, the bidirectional ac/dc converter plays an important role in the renewable energy system. When DERs have enough power, the energy from the dc bus can be easily transferred into the ac grid through the bidirectional ac/dc converter. In contrast, when the DER power does not have enough energy to provide electricity to the load in the dc bus, the bidirectional ac/dc converters can simultaneously and quickly change the power flow direction (PFD) from ac grid to dc grid and give enough power to the dc load and energy storage system. There are many requirements for ac/dc PWM converters as utility interface in a grid-tied system; for instance, providing power factor correction functions [4], [5], [7], low distortion line currents [1], [3], [7], high-quality dc output voltage [2], [9], and bidirectional power flow capability [8], [10], [11], [25]. Moreover, PWM converters are also suitable for modular system design and system reconfiguration. In this paper, a novel PWM control strategy with feedforward control scheme of a bidirectional single-phase ac/dc converter is presented.

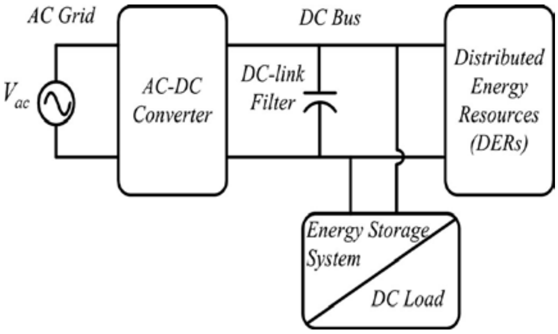


Fig. 1 Distribution energy system

In the existing PWM control strategies of a single-phase ac/dc converter, the converter switches are operated at higher frequency than the ac line frequency so that the switching harmonics can be easily removed by the filter [1], [3], [7]. The ac line current waveform can be more sinusoidal at the expense of switching losses. Until now several PWM strategies have been utilized in a single-phase ac/dc converter such as bipolar PWM (BPWM), unipolar PWM (UPWM) [12]–[14], HPWM [15]–[18], and Hysteresis switching [3], [19]–[24]. UPWM results in a smaller ripple in the dc side current and significantly lower ac side harmonic content [14] compared to the BPWM. The UPWM effectively doubles the switching frequency in the ac voltage waveform harmonic spectrum allowing the switching harmonics to be easily removed by the passive filter. The HPWM [16]–[18] utilizes two of the four switches modulated at high frequency and utilizes the other two switches commutated at the (low) output frequency to reduce the switching frequency and achieve better quality output. However, the switching loss in the HPWM is still the same as that of the UPWM [16]. The hysteresis switching method utilizes hysteresis in comparing the actual voltage and/or current to the reference. Although the hysteresis switching method has the advantages of simplicity and robustness [3], [20]–[24], the converters' switching frequency depends largely on the load parameters, and consequently, the harmonic ripples are not optimal. Hysteresis control methods [3], [20]–[24] with constant switching frequency have recently been presented. Those are usually based on the voltage and/or current error zero-crossing time to achieve a constant switching frequency. However, the capacitor ripple voltage and inductor ripple current are assumed to be ignored and the implemented inductor and/or capacitor are not very practical. The switching frequency jitter [3] problem would occur during the inverter dead-time control (i.e., dead time effects) in the hysteresis modulation.

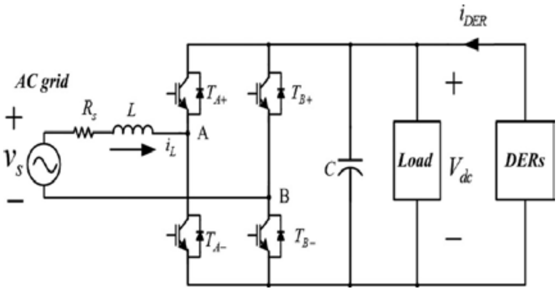


Fig. 2 Application of a bidirectional single-phase ac/dc converter in the renewable energy system

The simplified PWM requires only one active switch to change status during the switching period. In contrast, the conventional UPWM and/or BPWM require four active switches to change statuses during the switching period. There is no switching frequency jitter problem [3], [19]–[21] compared to hysteresis control methods in the simplified PWM strategy. A novel feedforward control scheme is also developed so that both the rectifier and inverter mode can be operated in a good manner. It is worth mentioning that the proposed feedforward control scheme is also suitable for the conventional UPWM and BPWM to provide fast output voltage response as well as improve input current shaping.

One problem associated with many existing drive systems with frequent regeneration is that the size of the dc link capacitor is often very large in order to limit the link voltage. Normally, a large capacitor bank of thousands of micro-Farad is required. The large capacitor bank not only increases the size and weight of the converter equipment, but also the equipment cost. If a braking resistor is used to dissipate the regenerative energy, the overall efficiency of the drive system becomes low. In order to reduce the link capacitor, a bidirectional switched-mode rectifier can be used so that regenerative energy can be absorbed by the supply instead of being stored in large capacitor bank or dissipated in a braking resistor. With the bidirectional feature, the switched mode converter concept originally developed for switched mode power supplies can now be employed in electronic drive systems.

2. OPERATION PRINCIPLE OF THE SIMPLIFIED PWM STRATEGY

A bidirectional single-phase ac/dc converter is usually utilized as the interface between DERs and the ac grid system to deliver power flows bidirectionally and maintains good ac current shaping and dc voltage regulation, as shown in Fig. 2. Good current shaping can avoid harmonic pollution in an ac grid system, and good dc voltage regulation can provide a high-quality dc load.

TABLE I
RECTIFIER MODE SWITCHING COMBINATION IN THE SIMPLIFIED PWM

	Status	T_{A+}	T_{A-}	T_{B+}	T_{B-}	Inductor status
$v_s > 0$	A	OFF	OFF	ON	OFF	$v_L > 0$
	B	OFF	ON	OFF	OFF	
	E	OFF	OFF	OFF	OFF	$v_L < 0$
$v_s < 0$	C	ON	OFF	OFF	OFF	$v_L < 0$
	D	OFF	OFF	OFF	ON	
	E	OFF	OFF	OFF	OFF	$v_L > 0$

TABLE II
INVERTER MODE SWITCHING COMBINATION IN THE SIMPLIFIED PWM

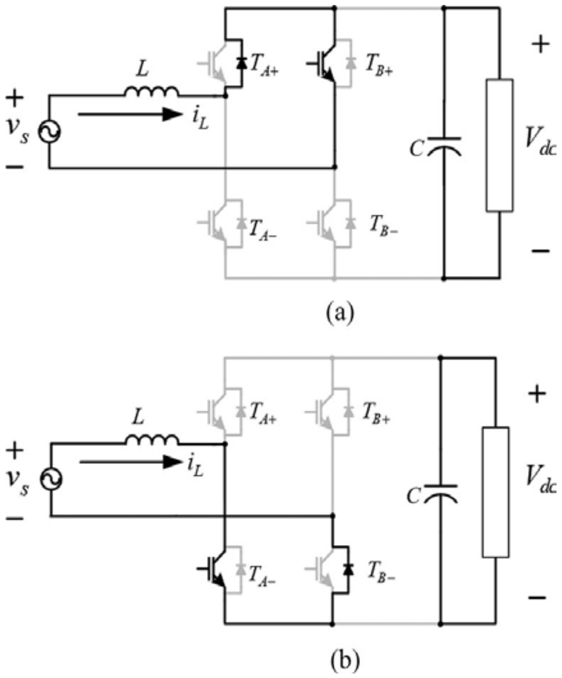
	Status	T_{A+}	T_{A-}	T_{B+}	T_{B-}	Inductor status
$v_s > 0$	F	ON	OFF	OFF	OFF	$v_L > 0$
	G	OFF	OFF	OFF	ON	
	H	ON	OFF	OFF	ON	$v_L < 0$
$v_s < 0$	I	OFF	ON	OFF	OFF	$v_L < 0$
	J	OFF	OFF	ON	OFF	
	K	OFF	ON	ON	OFF	$v_L > 0$

To achieve bidirectional power flows in a renewable energy system, a PWM strategy may be applied for the single-phase full-bridge converter to accomplish current shaping at the ac side and voltage regulation at the dc side. Generally, BPWM and UPWM strategies are often utilized in a single-phase ac/dc converter. In this paper, a novel simplified PWM strategy is proposed. The simplified PWM only changes one active switch status in the switching period to achieve both charging and discharging of the ac side inductor current. Therefore, the simplified PWM strategy reduces the switching losses and also provides high conversion efficiency. The switching statuses of the simplified PWM are listed in Tables I and II for rectifier mode and inverter mode operation, respectively. Both the rectifier and inverter mode operations of the simplified PWM strategies are explained in this section as follows.

A. Rectifier Mode

Consider the single-phase system shown in Fig. 2 and assume the ac grid system internal impedance is highly inductive and, therefore, represented by L. The equivalent series resistance of L is neglected. Consider the converter is operated in the rectifier mode. While ac grid voltage source is operating in the positive half-cycle vs > 0, the operating circuits of Statuses A and B listed in Table I of the simplified PWM are shown in Fig. 3(a) and (b), respectively. Using Kirchhoff's voltage law in the circuit operation shown in Fig. 3(a) and (b), the voltage relationship can be obtained as follows:

$$v_s - L\frac{d}{dt}i_L = 0. \tag{1}$$



(a)

(b)

Fig. 3 Operation circuit of the simplified PWM operated in the rectifier mode under (a) Status A and (b) Status B, while vs > 0 and iL > 0

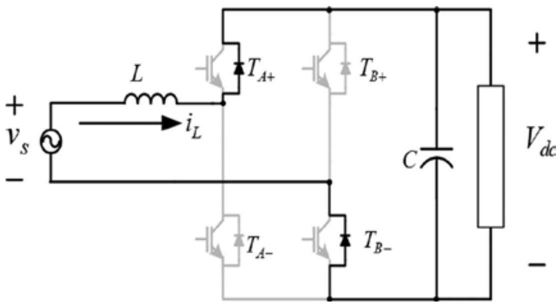


Fig. 4 Operation circuit of the simplified PWM operated in the rectifier mode under Status E, while vs > 0 and iL > 0

One can see that while vs > 0, the inductor current is increasing in both Statuses A and B, and the voltage across the inductor is vs . Therefore, in this condition, the inductor current is in the charging state.

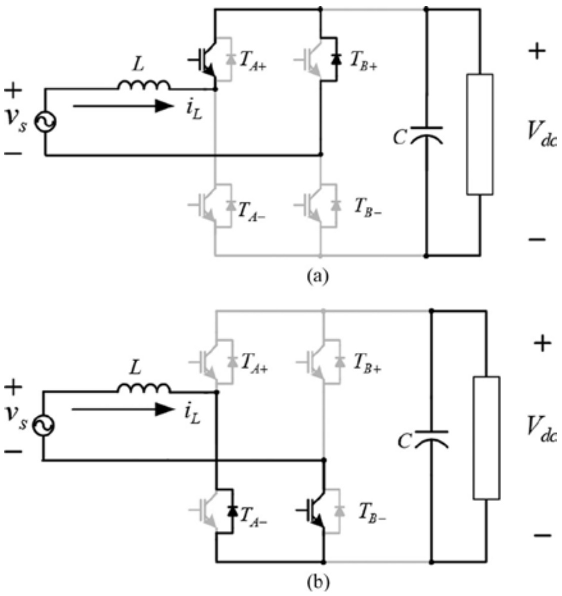
While the converter is in Status E, as shown in Fig. 4, all of the switches are turned OFF. Using Kirchhoff's voltage law in the circuit operation shown in Fig. 4, the voltage relationship can be obtained as follows:

$$v_s - L\frac{d}{dt}i_L - V_{\text{dc}} = 0. \tag{2}$$

The inductor voltage is vs − Vdc, which decreases the inductor current. Therefore, in this condition, the inductor current is in the discharging state.

Consider the ac grid voltage source during the negative half cycle vs < 0 in Fig. 2. The operating circuits of Statuses C and D of the simplified PWM are shown in Fig. 5(a) and (b), respectively. Using Kirchhoff's voltage law in the circuit operation shown in Fig. 5, the voltage relationship can be obtained as follows:

$$v_s - L\frac{d}{dt}i_L = 0. \tag{3}$$



(a)

(b)

Fig. 5 Operation circuit of the simplified PWM operated in the rectifier mode under (a) Status C and (b) Status D, while vs < 0 and iL < 0

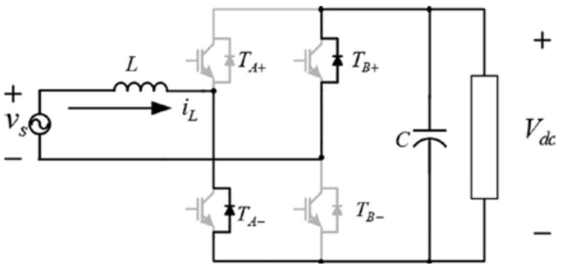


Fig. 6 Operation circuit of the simplified PWM operated in the rectifier mode under Status E, while vs < 0 and iL < 0

One can see that while the ac grid voltage source is operating in the negative half-cycle vs < 0, the inductor current is decreasing in both Statuses C and D. The voltage across the inductor L is vs . Therefore, in this condition, the inductor current is in the discharging state.

While the converter is in Status E, as shown in Fig. 6, all of the switches are turned OFF. Using Kirchhoff's voltage law in the circuit operation shown in Fig. 6, the voltage relationship can be obtained as follows:

$$v_s - L\frac{d}{dt}i_L + V_{\mathrm{dc}} = 0. \tag{4}$$

The inductor voltage is vs + Vdc, which increases the inductor current. Therefore, in this condition, the inductor current is in the charging state.

In summary, while ac grid voltage source is operating in the positive half-cycle vs > 0, both Statuses A and B increase the inductor current and Status E decreases the inductor current to achieve ac current shaping and dc voltage regulation. While the ac grid voltage source is operating in the negative half-cycle vs < 0, both Statuses C and D decrease the inductor current and Status E increases the inductor current to accomplish ac current shaping and dc voltage regulation. Regardless whether the ac grid voltage source is operating in the positive half-cycle vs > 0 or negative half-cycle vs < 0, the converter inductor current can be increased or decreased properly in the simplified PWM operated in the rectifier mode.

B. Inverter Mode

The switching combination of the simplified PWM operated in the inverter mode is listed in Table II. When the converter is operated in the inverter mode, the actual inductor current is in the reverse direction compared to the ac grid voltage. Consider the ac grid voltage source is operating in the positive half-cycle vs > 0; the input current is in the reverse direction iL < 0.Both Statuses F and G give inductor L positive voltage to charge the inductor current. The corresponding circuit operation of Statuses F and G is shown in Fig. 7. Status H gives inductor L negative voltage to discharge the inductor current, as shown in Fig. 8.

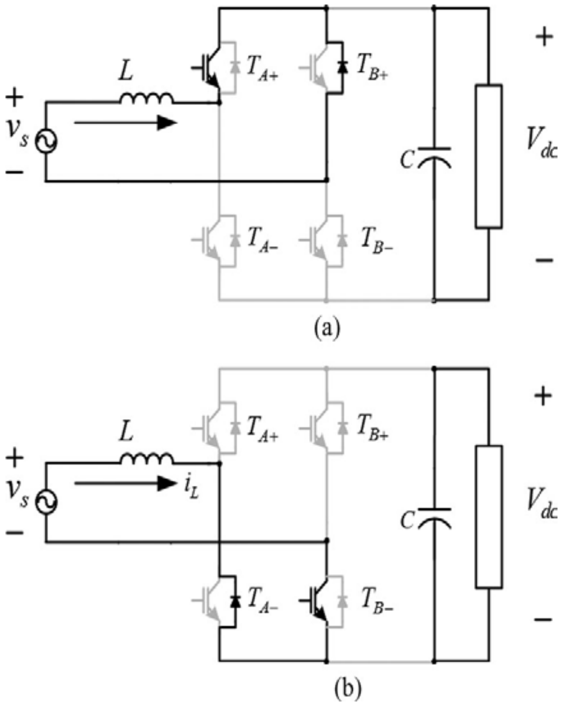


Fig. 7 Operation circuit of the simplified PWM operated in the inverter mode under (a) Status F and (b) Status G, while vs > 0and iL < 0

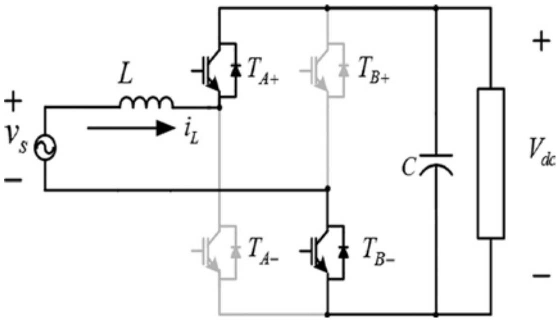


Fig. 8 Operation circuit of the simplified PWM operated in the inverter mode under Status H, while vs > 0 and iL < 0

While the ac grid voltage source is operating in the negative half-cycle vs < 0, the input current is in the reverse direction iL > 0. Both Statuses I and J give inductor L negative voltage to discharge the inductor current. The corresponding circuit operation of Statuses I and J is shown in Fig. 9. Status K gives inductor L positive voltage to charge the inductor current, as shown in Fig. 10. Regardless of whether the ac grid voltage source is operating in the positive half-cycle vs > 0 or the negative half cycle vs < 0, the converter inductor current can be increased or decreased properly to achieve ac current shaping and dc voltage regulation in the simplified PWM operated in the inverter mode.

According to the previous discussion, the ac grid line current of a single-phase ac/dc PWM converter could be increased and decreased easily in both rectifier and inverter mode to achieve bidirectional power flows and proper line current shaping and voltage regulation in the simplified PWM strategy.

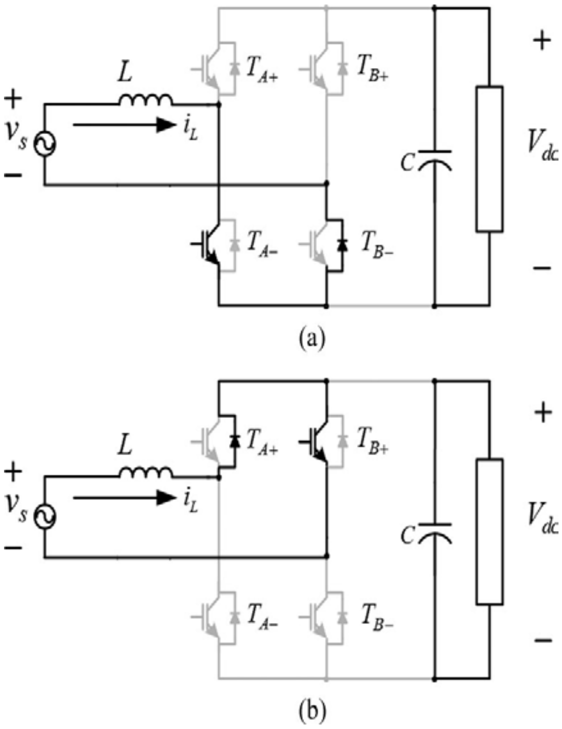


Fig. 9 Operation circuit of the simplified PWM operated in the inverter mode under (a) Status I and (b) Status J, while *vs* < 0 and *iL* > 0.

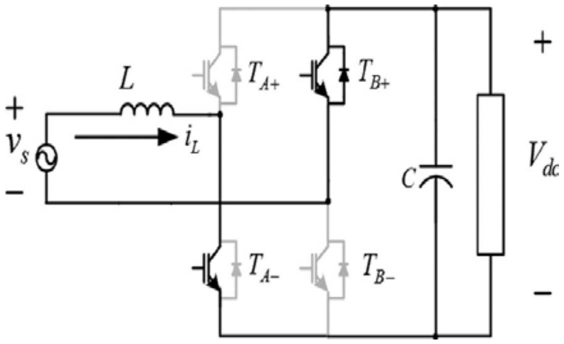


Fig. 10 Operation circuit of the simplified PWM operated in the inverter mode under Status K, while *vs* < 0 and *iL* > 0.

3. PROPOSED POWER FACTOR CORRECTION CIRCUIT

POWER FACTOR is the ratio between the useful (true) power (kW) to the total (apparent) power (kVA) consumed by an item of a.c. electrical equipment or a complete electrical installation. It is a measure of how efficiently electrical power is converted into useful work output. The ideal power factor is unity, or one.

All current flow causes losses both in the supply and distribution system. A load with a power factor of 1.0 results in the most efficient loading of the supply. A load with a power factor of, say, 0.8, results in much higher losses in the supply system and a higher bill for the consumer. A comparatively small improvement in power factor can bring about a significant reduction in losses since losses are proportional to the square of the current. When the power factor is less than one the ‘missing’ power is known as reactive power which unfortunately is necessary to provide a magnetizing field required by motors and other inductive loads to perform their desired functions. Reactive power can also be interpreted as wattless, magnetizing or wasted power and it represents an extra burden on the electricity supply system and on the consumer’s bill. A poor power factor is usually the result of a significant phase difference between the voltage and current at the load terminals, or it can be due to a high harmonic content or a distorted current waveform. A poor power factor is generally the result of an inductive load such as an induction motor, a power transformer, a ballast in a luminaire, a welding set or an induction furnace. A distorted current waveform can be the result of a rectifier, an inverter, a variable speed drive, a switched mode power supply, discharge lighting or other electronic loads. A poor power factor due to inductive loads can be improved by the addition of power factor correction equipment, but a poor power factor due to a distorted current waveform requires a change in equipment design or the addition of harmonic filters. Some inverters are quoted as having a power factor of better than 0.95 when, in reality, the true power factor is between 0.5 and 0.75. The figure of 0.95 is based on the cosine of the angle between the voltage and current but does not take into account that the current waveform is discontinuous and therefore contributes to increased losses. An inductive load requires a magnetic field to operate and in creating such a magnetic field causes the current to be out of phase with the voltage (the current lags the voltage). Power factor correction is the process of compensating for the lagging current by creating a leading current by connecting capacitors to the supply. A sufficient capacitance is connected so that the power factor is adjusted to be as close to unity as possible. The basic configuration of power factor correction circuit is shown in figure.

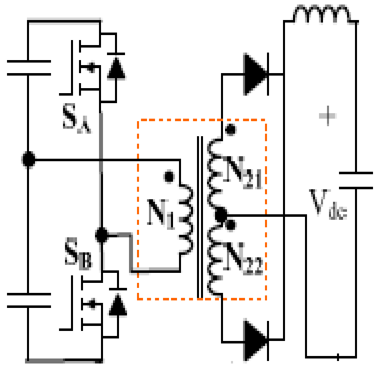


Fig. 11 General Configuration of Power Factor Correction Circuit

4. FEEDFORWARD CONTROL SCHEME FOR BIDIRECTIONAL AC/DC CONVERTER

Based on the simplified PWM, a novel feedforward control scheme is presented in this section. For a convenient explanation, the converter operated in the rectifier mode is discussed first. The rectifier mode switching combination is listed in Table I. One can choose operation Statuses A and E during the condition *vs* > 0, and Statuses C and E during the condition *vs* < 0. It should be noted that the selection of Status A or B for increasing inductor current and Status C or D for decreasing inductor current is all allowable in the simplified PWM strategy.

To derive the state-space averaged equation for the simplified PWM strategy, the duty ratio *D*on is defined as *D*on = *t*on/*T* , where *t*on is the time duration when the switch is turned ON, i.e., *S*on = 1, and *T* is the time period of triangular waveform. The duty ratio *D*off is defined as *D*off = 1− *D*on, which is the duty ratio when the switch is turned OFF. While the ac grid voltage source is operating in the positive half-cycle *vs* > 0, the switching duty ratio of Status A is defined as *D*on and that of Status E is defined as *D*off . The corresponding circuit equations of Statuses A and E were obtained in (1) and (2), respectively. By introducing the state-space averaged technique and volt–second balance theory, the state-space averaged equation is derived as follows:

$$v_s - (1 - D_{\mathrm{on}})\, V_{\mathrm{dc}} = 0.$$

When the converter is operated in the steady state, the dc voltage is equal to the desired command *V*dc = *V* dc; (12) can also be expressed in the following form:

$$D_{\mathrm{on}} = \left(1 - \frac{v_s}{V^*_{\mathrm{dc}}}\right)$$

While the ac grid voltage source is operating in the negative half-cycle *vs* < 0, the duty ratios corresponding to Statuses E and C are *D*on and *D*off , respectively. The corresponding circuit equations for Statuses E and C were obtained in (4) and (3), respectively. By introducing the state-space averaged technique and volt–second balance theory, the state-space averaged equation is derived as follows, while the ac grid voltage source is operating in the negative half-cycle *vs* < 0:

$$v_s + D_{\text{on}} V_{\text{dc}} = 0.$$

Similarly, when the converter is operated in the steady state, the output voltage is equal to the desired command *V*dc = *V*dc. Equation (14) can be expressed in the following form:

$$D_{\text{on}} = -\frac{v_s}{V^*_{\text{dc}}}$$

According to the PWM properties, the switching duty ratio can be expressed in terms of the control signal *v*_cont and the peak value ˆvtri of the triangular waveform

$$D_{\text{on}} = \frac{v'_{\text{cont}}}{\hat{V}_{\text{tri}}}$$

Substituting (13) and (15) into (16), the switching duty ratios in both conditions *vs* > 0 and *vs* < 0 are derived

$$v'_{\text{cont}} = \begin{cases} \left(1 - \dfrac{v_s}{V^*_{\text{dc}}}\right)\hat{V}_{\text{tri}}, & \text{if } v_s > 0 \\ -\dfrac{v_s}{V^*_{\text{dc}}}\hat{V}_{\text{tri}}, & \text{if } v_s < 0. \end{cases}$$

Consider that the converter is operated in the inverter mode with the switching combination listed in Table II. One can choose Statuses F and H for increasing and decreasing the inductor current, respectively, during condition *vs* > 0, and Statuses I and K for decreasing and increasing the inductor current, respectively, during the condition *vs* < 0. Note that selecting Status F or G for increasing the inductor current and Status I or J for decreasing the inductor current is all allowable in the simplified PWM strategy. While the converter is operated in the inverter mode, the control signal *v*_cont can be obtained using a similar manner in the rectifier mode. After calculation, the control signal *v*_cont operated in the inverter mode is the same as that in the rectifier mode, as described in (17).

Because the control signal *v*cont is proportional to *D*on, one can regard the calculated signal *v*_cont in (17) as the duty ratio feedforward control signal *vf f* to add into the dual-loop feedback control signal *vf b*. The feedforward control signal *vf f* can enhance the control ability to provide fast output voltage response as well as improve current shaping. Thus, the developed control scheme for the simplified PWM is presented in Fig. 12. The detailed switching signal generator function is also shown in Fig. 13. The switching signal generator requires signals *S*on, the grid voltage sign (*vs*), and PFD combined with Tables I and II to generate switching signals TA+,TA−,TB+,TB−. It is worth mentioning that the proposed feedforward control scheme is suitable for both the simplified PWM strategy and the conventional BPWM and UPWM strategies.

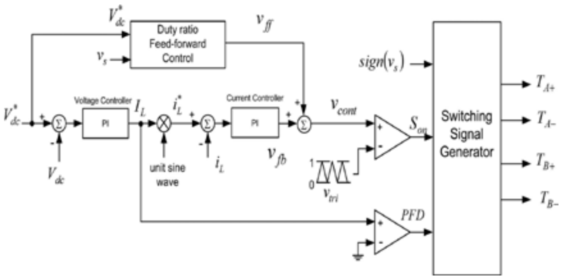


Fig. 12 Proposed control scheme for the simplified PWM strategy

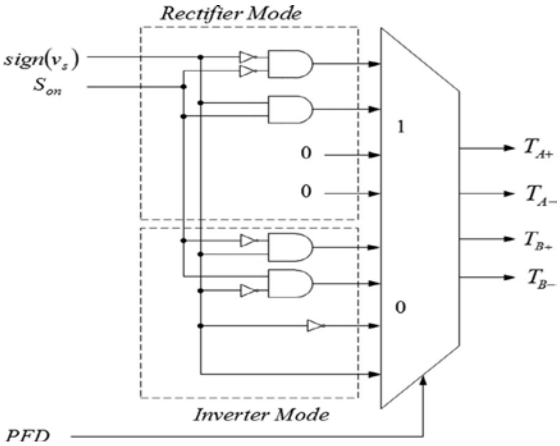


Fig. 13 Detailed function block of the switching signal generator

5. SIMULATION RESULTS

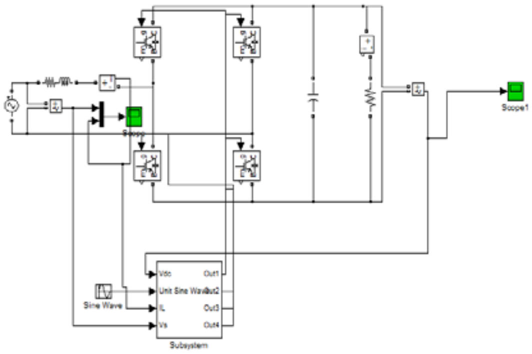


Fig. 14 Simulation of Bidirectional AC/DC Converter

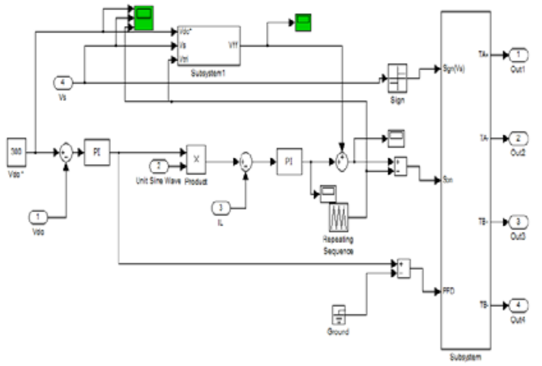


Fig. 15 Simulation of Feedforward Control Technique

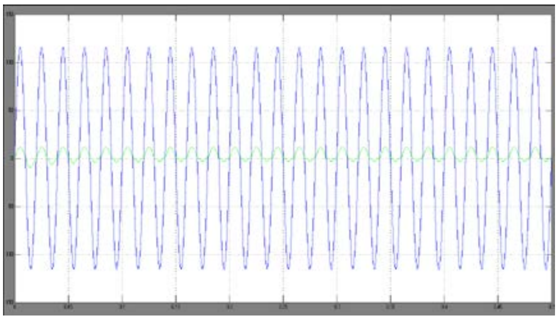


Fig. 16 Input Voltage and Current of AC/DC Converter

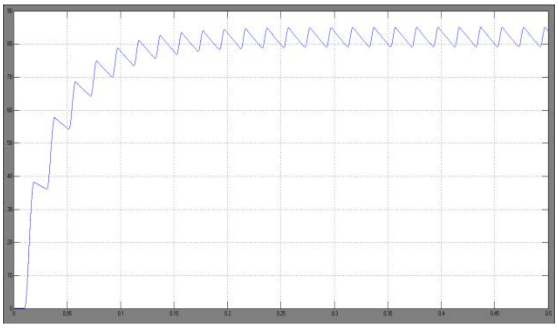


Fig. 17 Output DC Voltage of the AC/DC Converter

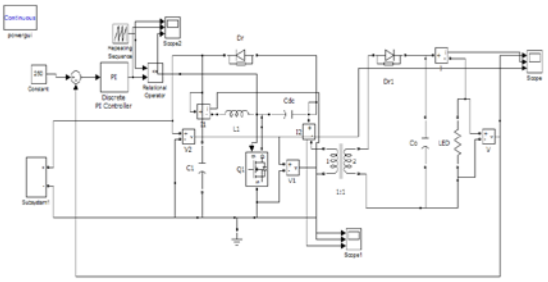


Fig. 18 Simulation of bidirectional AC/DC Converter with PFC Circuit

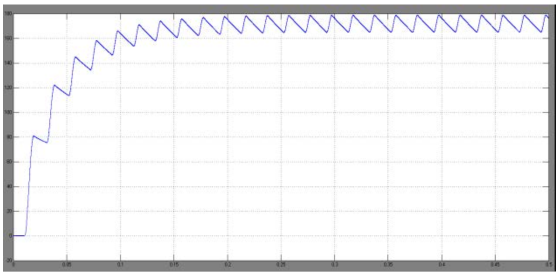


Fig. 19 Output DC Voltage of PFC Converter and Currents

6. CONCLUSION

The proposed PFC converter further improves the DC voltage of bidirectional AC/DC converter. This paper presented a simplified PWM strategy using a feedforward control scheme in the bidirectional single-phase ac/dc converter. The simplified PWM strategy only requires changing one active switch status in the switching period instead of changing four active switch statuses as required in the UPWM and BPWM strategies. The efficiency of an ac/dc converter operated in the simplified PWM strategy is higher than that in the UPWM and BPWM strategies. And its efficiency increased further when we used the proposed PFC converter with bidirectional AC/DC converter.

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